SLS Space Launch System

A Versatile Methodology that Developed the Friction Pull Plug Welding Process

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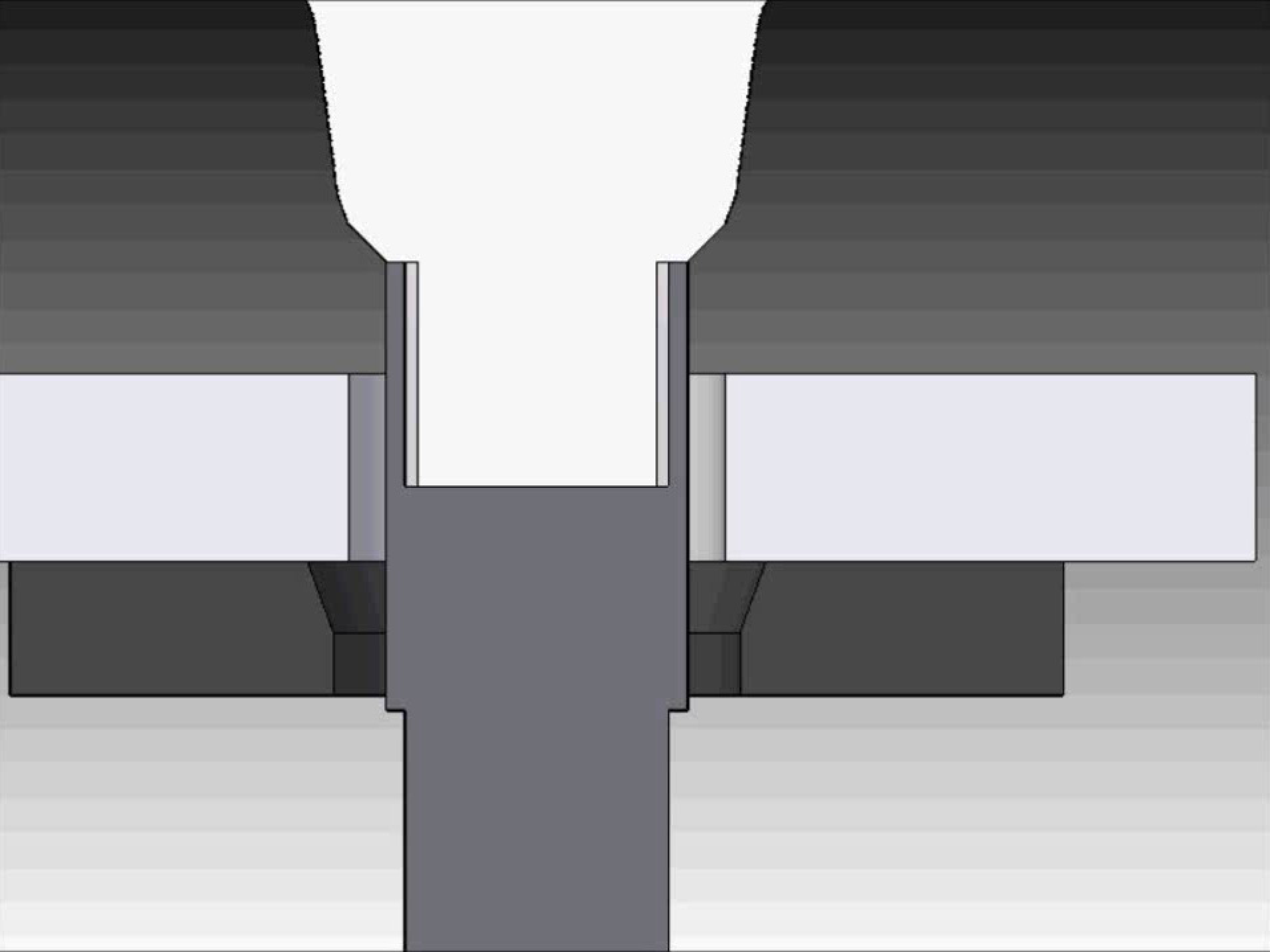
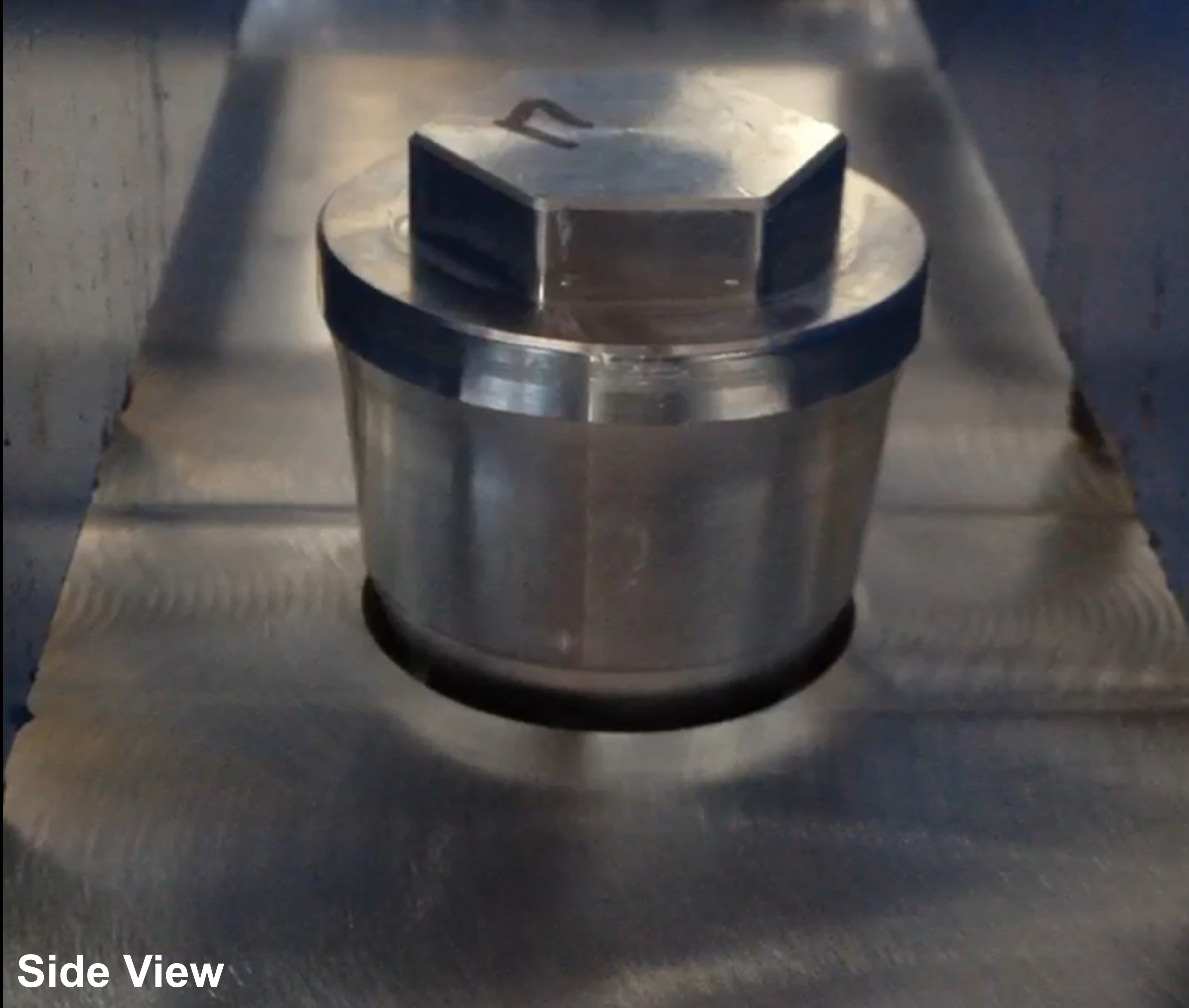



Side View


Top View


Side View

AGENDA

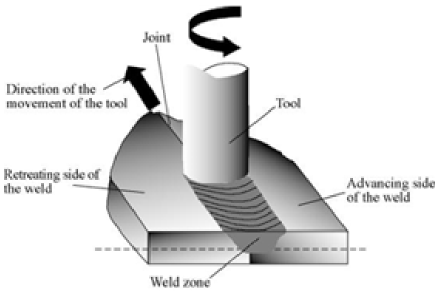
- ✓ **Background**
- ✓ **Development**
    - ✓Try To Fail
- ✓ **Optimization**
    - ✓Try to Succeed
- ✓ **Current Status**

Background

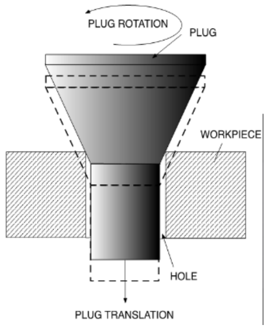
- **Why plug?**
  - To Close out Self-Reacting Friction Stir Welds (SR-FSW)
  - Risk reduction for repair scenario

- **What are the benefits of Friction Pull Plug Welds (FPPW) vs. Fusion?**
  - Repeatability (Automated process)
  - Higher mechanical properties (solid state process)

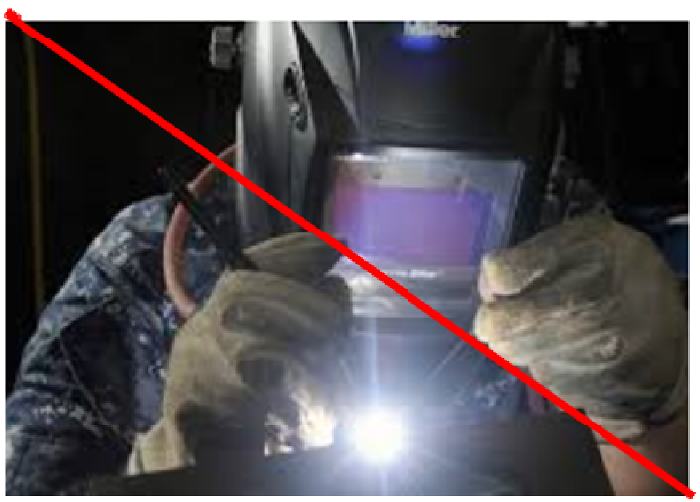
SR-FSW



FPPW



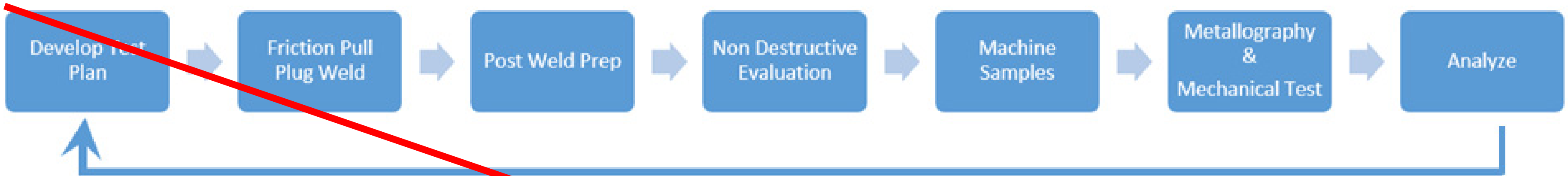
Fusion

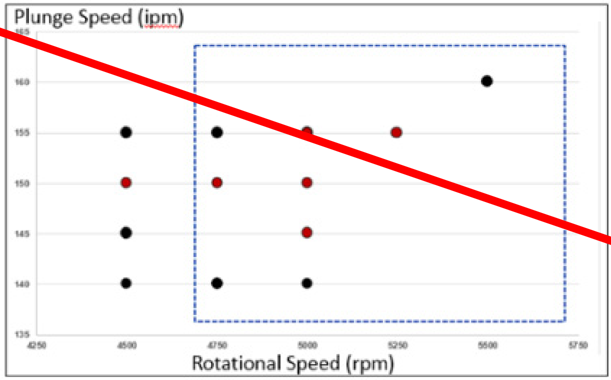


FPPW

Background

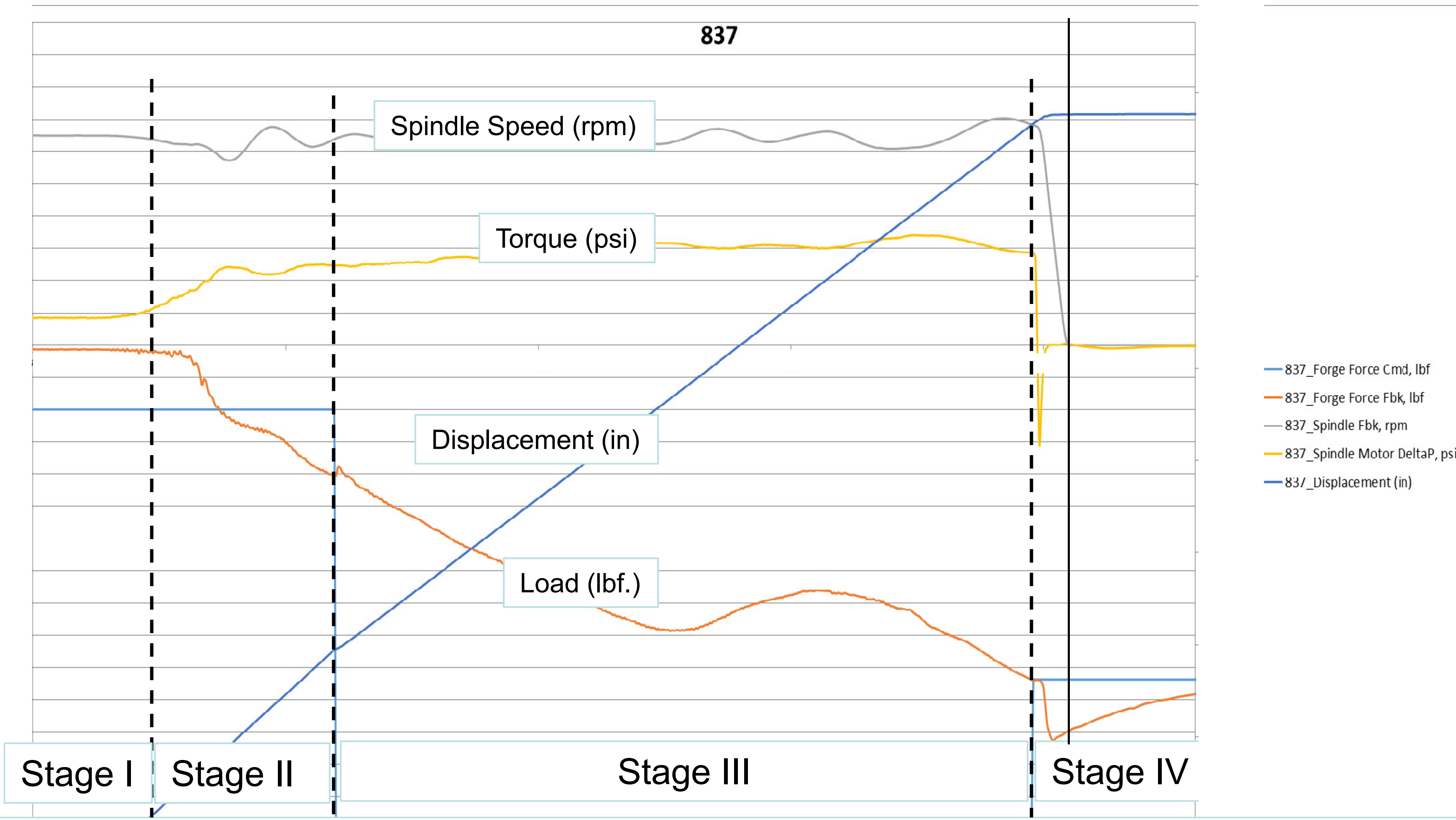
- ♦ **Development Project**
  - Current thickness experience: A
  - New developmental thickness: B = A(167%)
- ♦ **High Stakes, High Visibility**
- ♦ **Previous development methodology**





- ♦ **New Development Methodology: Start from scratch and try to fail.**

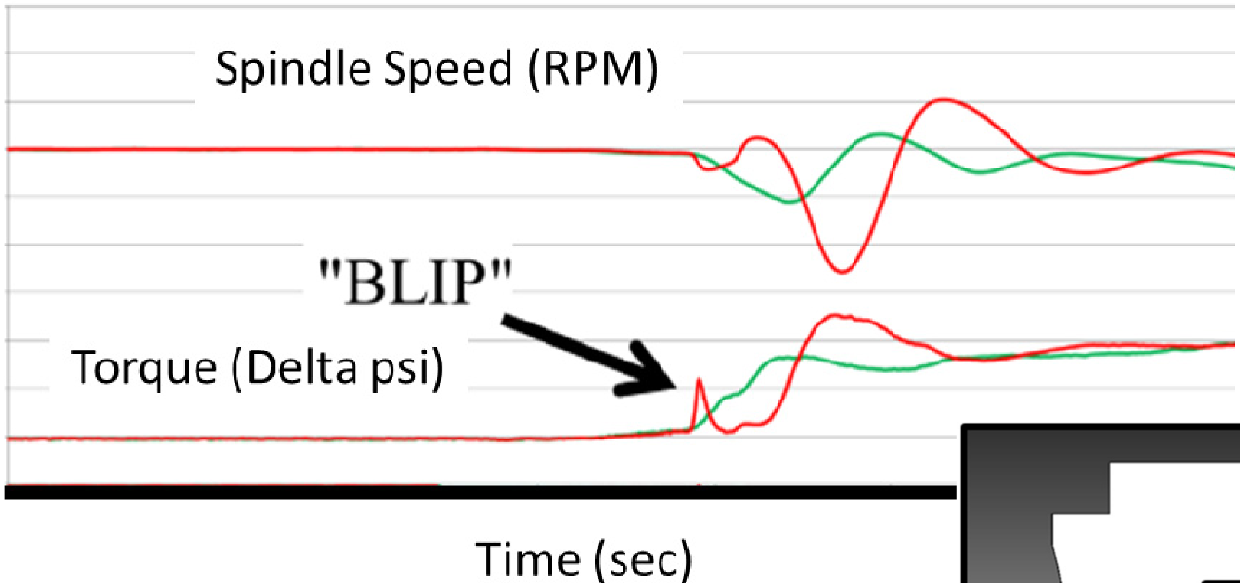
Process Development Methodology: Tool Feedback

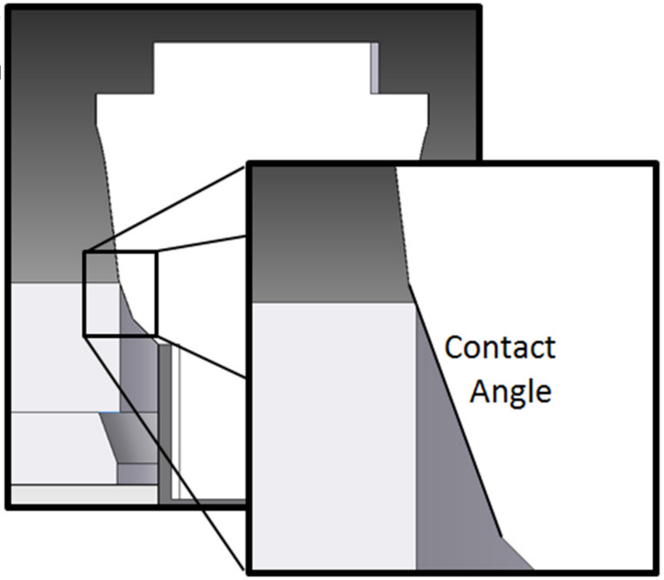


Stage I – Contact (consistency)
Stage II – Torque Management (minimize torque peak and spindle rpm fluctuation)
Stage III - Manage Heat input (prevent necking)
Stage IV - Maintain forging pressure (tool dynamics)

Development
Stage 1: "Contact"

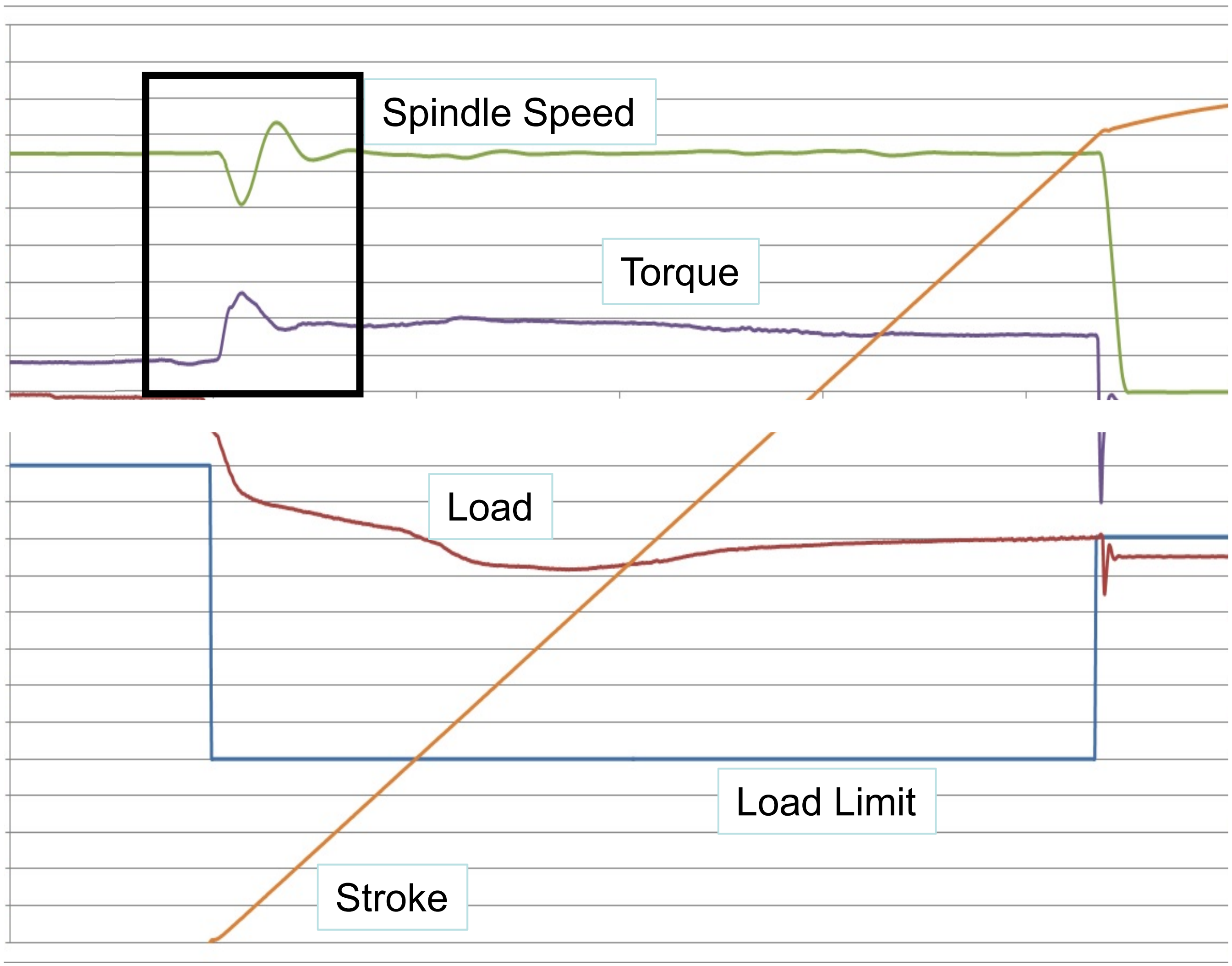
- Greatest obstacle for Stage 1: consistency.
- Solution: Contact Angle

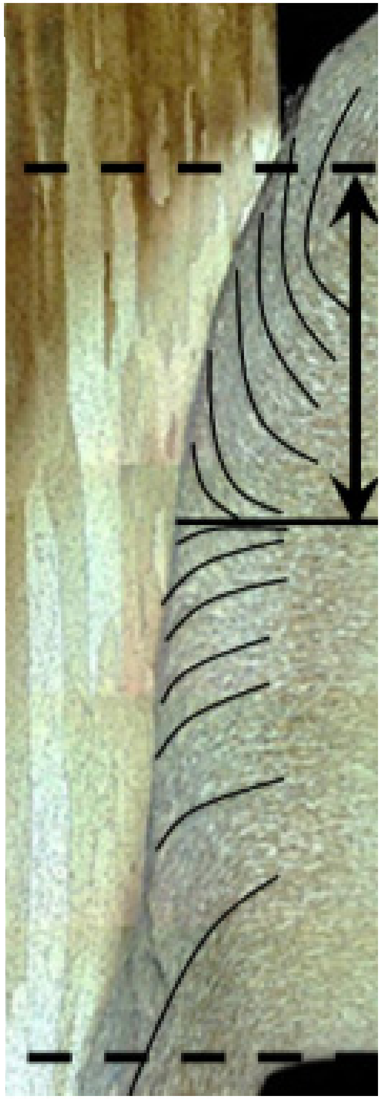




Development Stage 2: "Torque Hump"

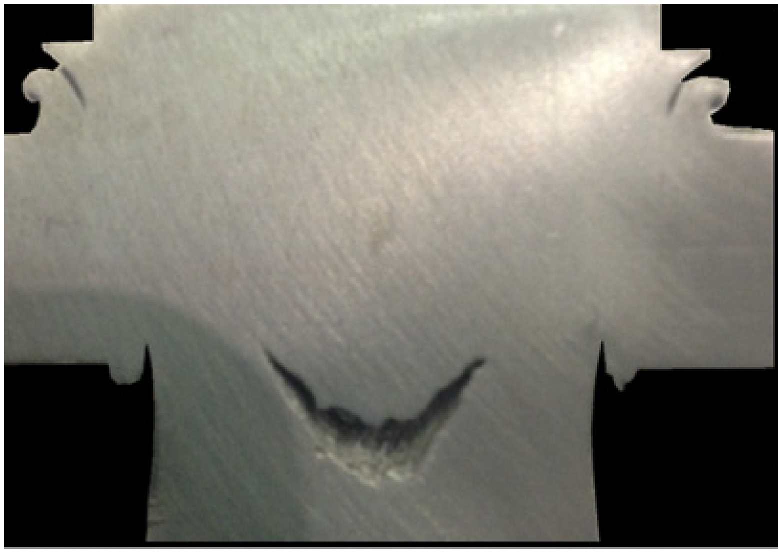
- Greatest obstacle for Stage 2: Not stalling the machine.
- Solution: Two speed process



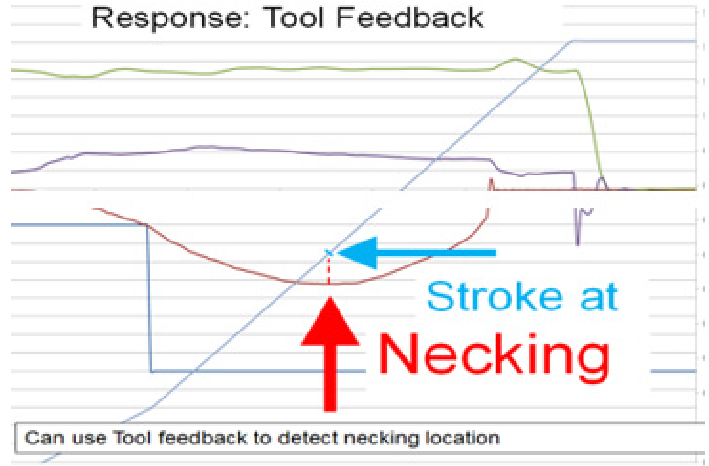


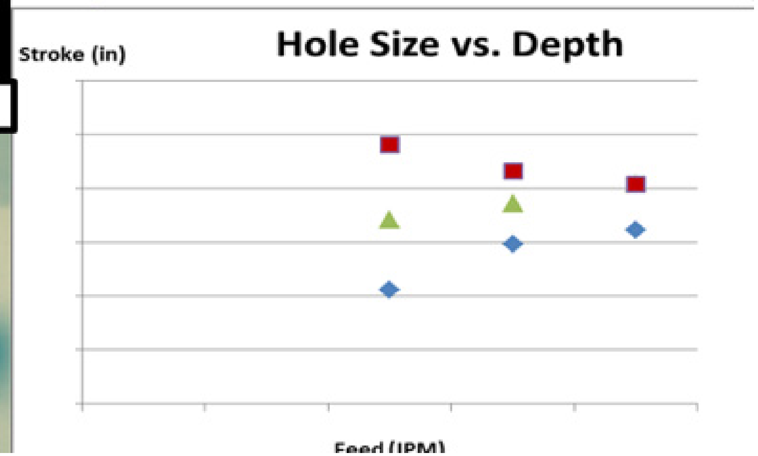
Development
Stage 3: “Heat Management”

- Greatest obstacle for Stage 3: Necking
- Solution: Larger Plug



Necking causes the plug to loose its structural integrity

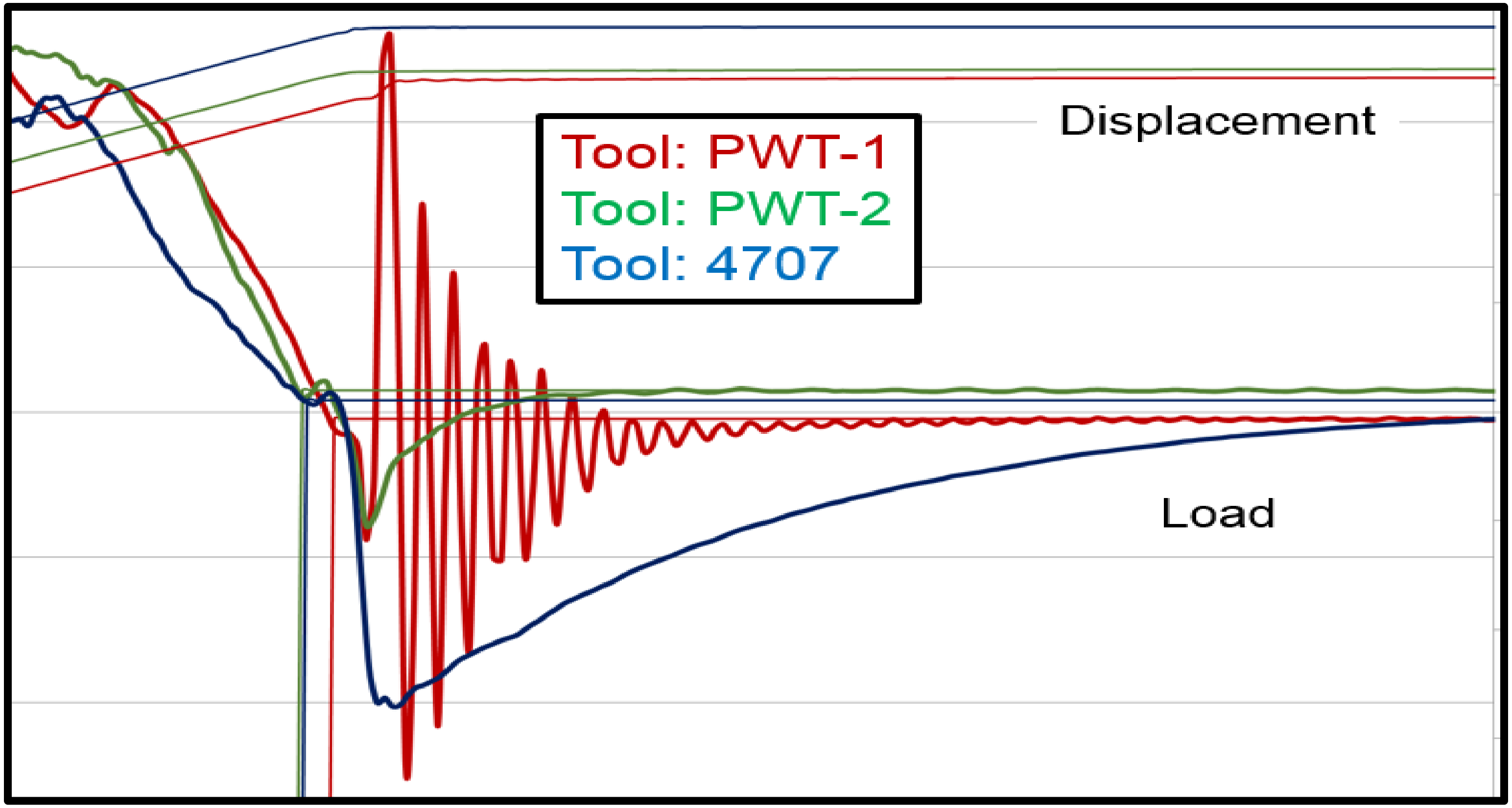




Using the methodology of Tool Feedback and wisdom through failures enabled the project to quantify and overcome the Necking issue

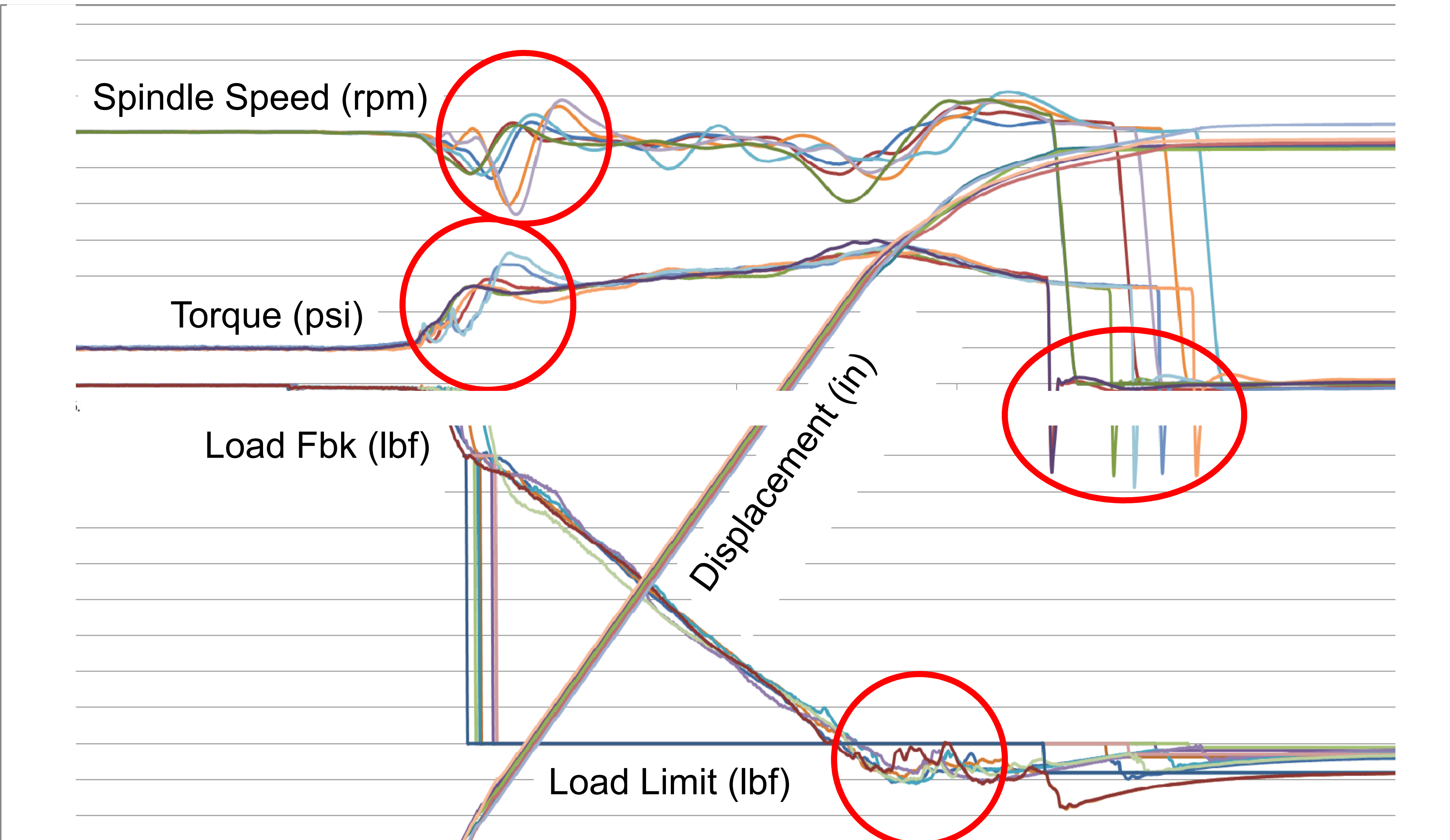
Development
Stage 4: "Forging Load"

- Greatest obstacle for Stage 4: Tool Performance
- Solution: Tuning with respect to process parameters



SLS
Space Launch System

Optimization
First Attempt - Tool Feedback

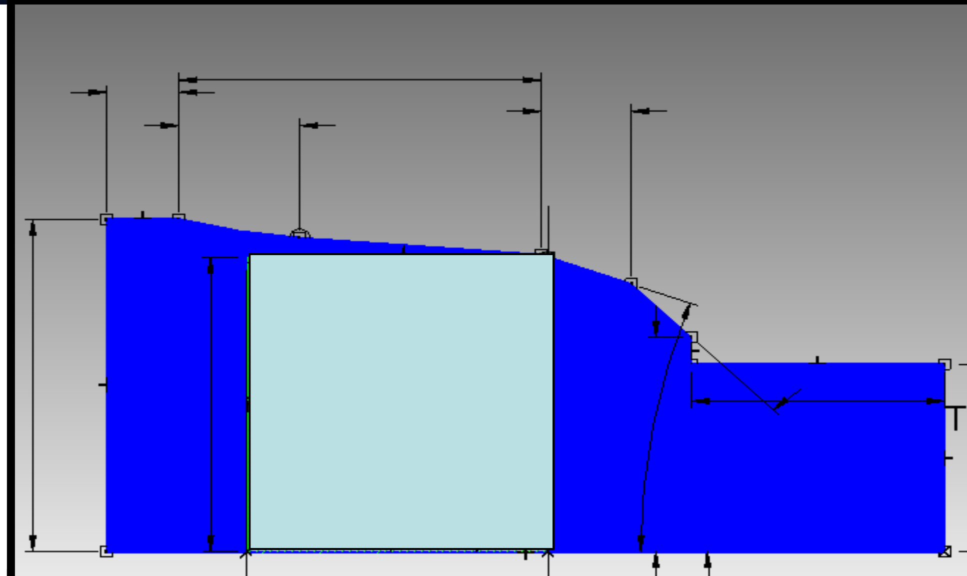


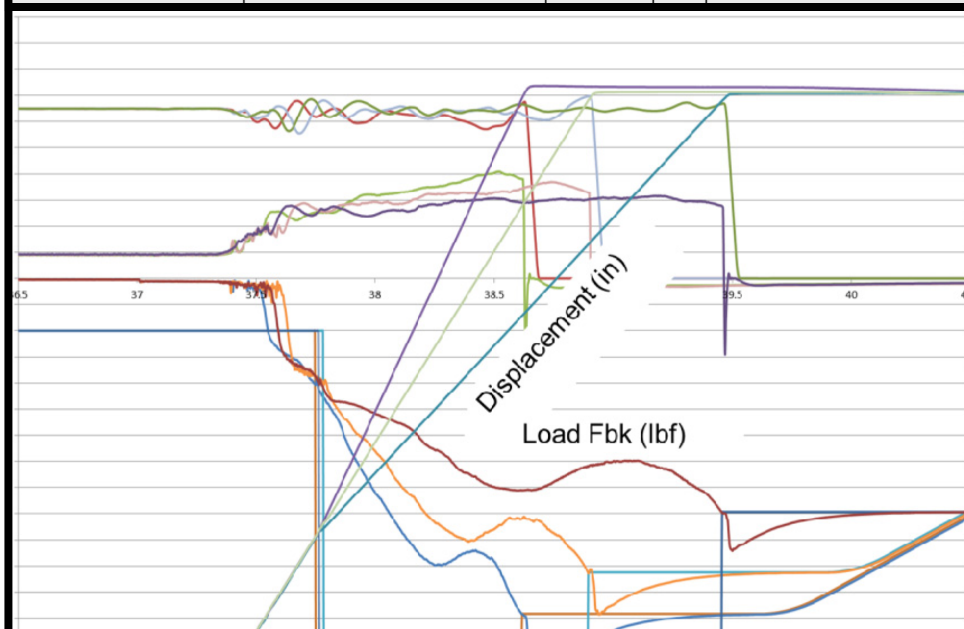
Variability in Spindle Speeds, Torque Humps, Load Limits, Process Durations and Mechanical Test Results

Space Launch System

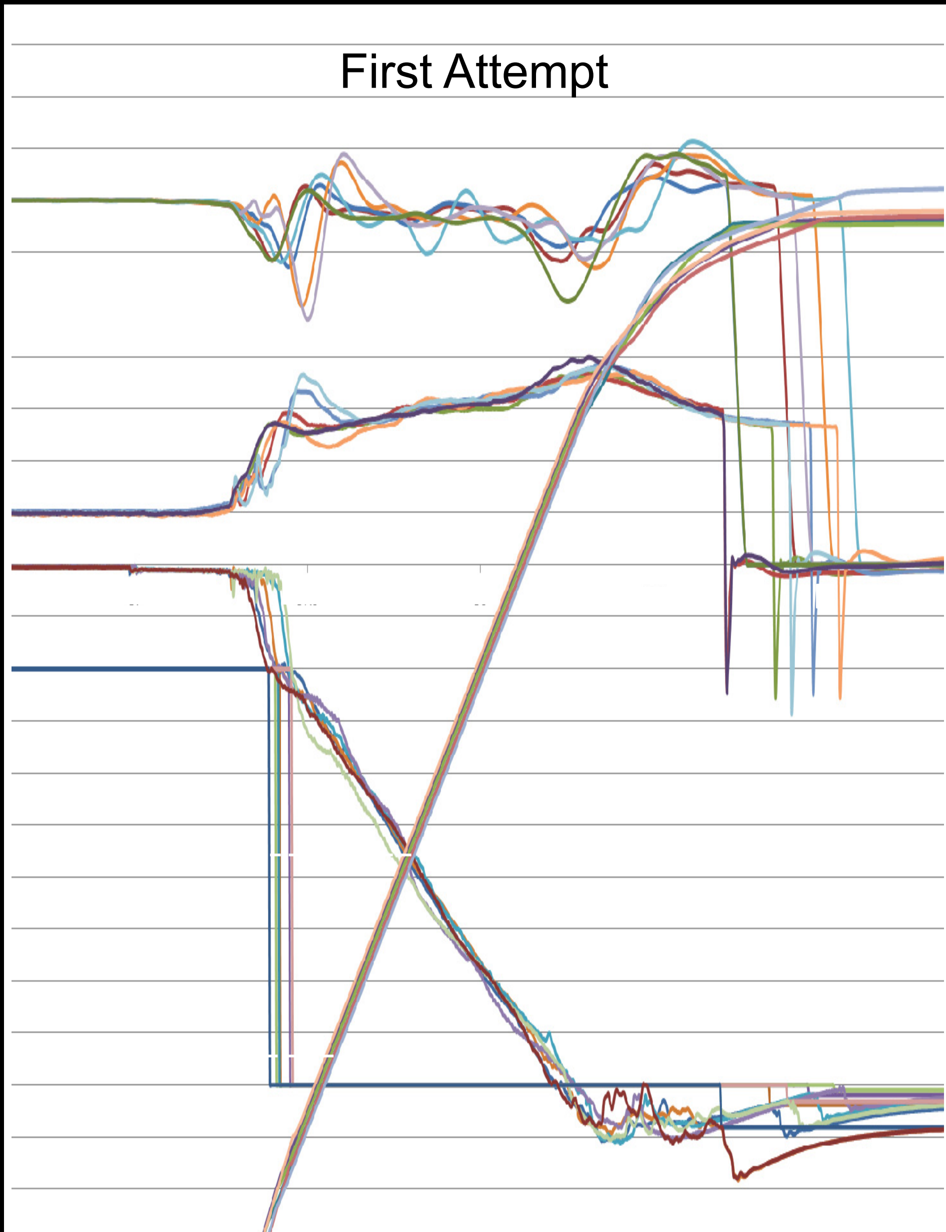
Optimization
Reverse Engineer Plug and Process

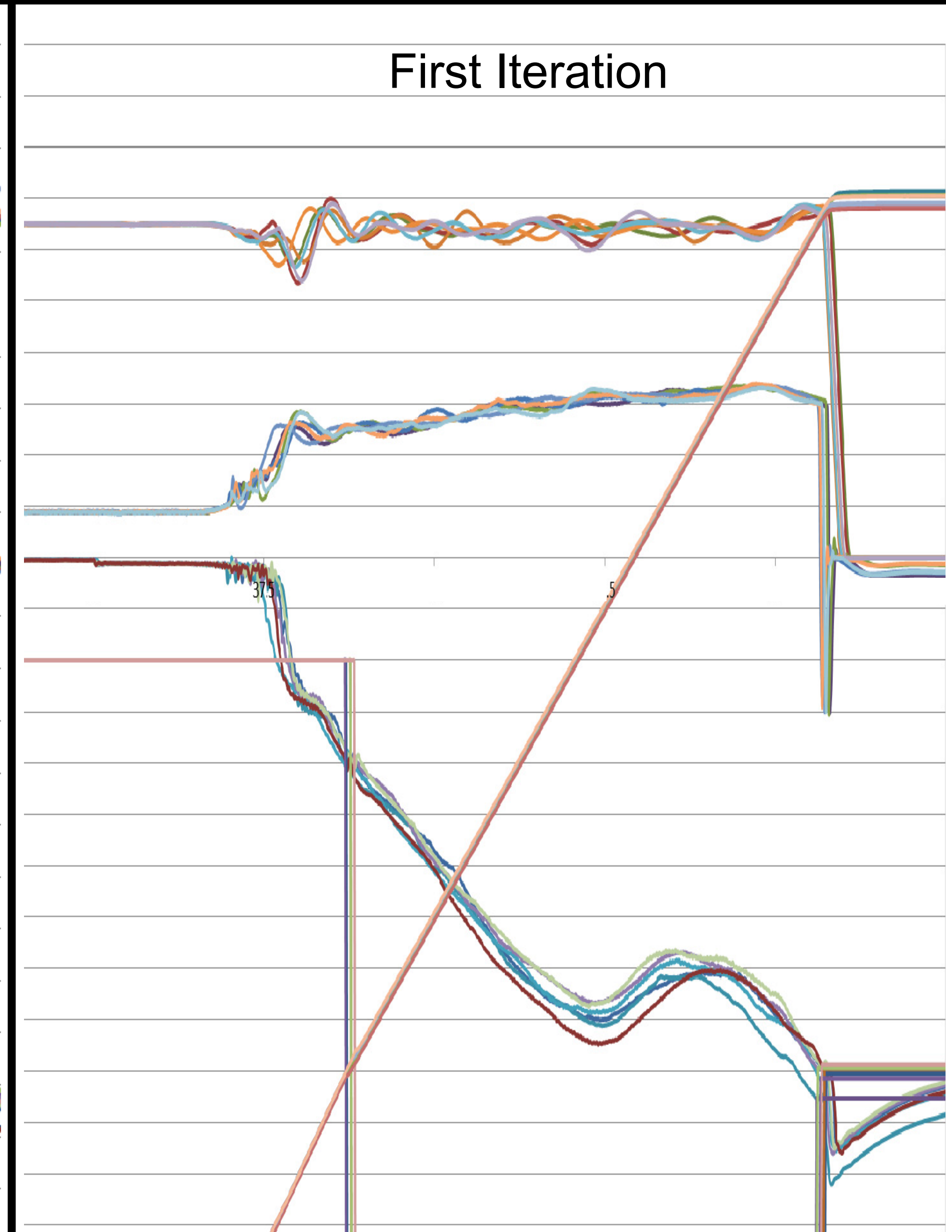
- ✓ **Redesigned the plug**
  - ✓Angle
  - ✓Contact angle
  - ✓Diameter
  - ✓Major diameter Radius
- ✓ **Redesigned the Process**
  - ✓Lowered RPMs
  - ✓Changed the trigger load
  - ✓Back calculated the stroke speed based on a desired load
  - ✓Eliminated the load limit





Optimization
First Iteration – Tool Feedback





Optimization
First Iteration - Results

Welding	NDE (Dye-Pen)	Macros	Mechanical Test
• No Stalls • Consistent Tool Feedback	No defects or even indications	<u>Beautiful</u> No Melting, Inclusions, Voids or Cracks	• Plugs as Strong as the Initial Welds • No specimen width effects • LN2 Cryo ENH of 1.2 • LH2 Cryo ENH of 1.4

Incomparably Great Results!

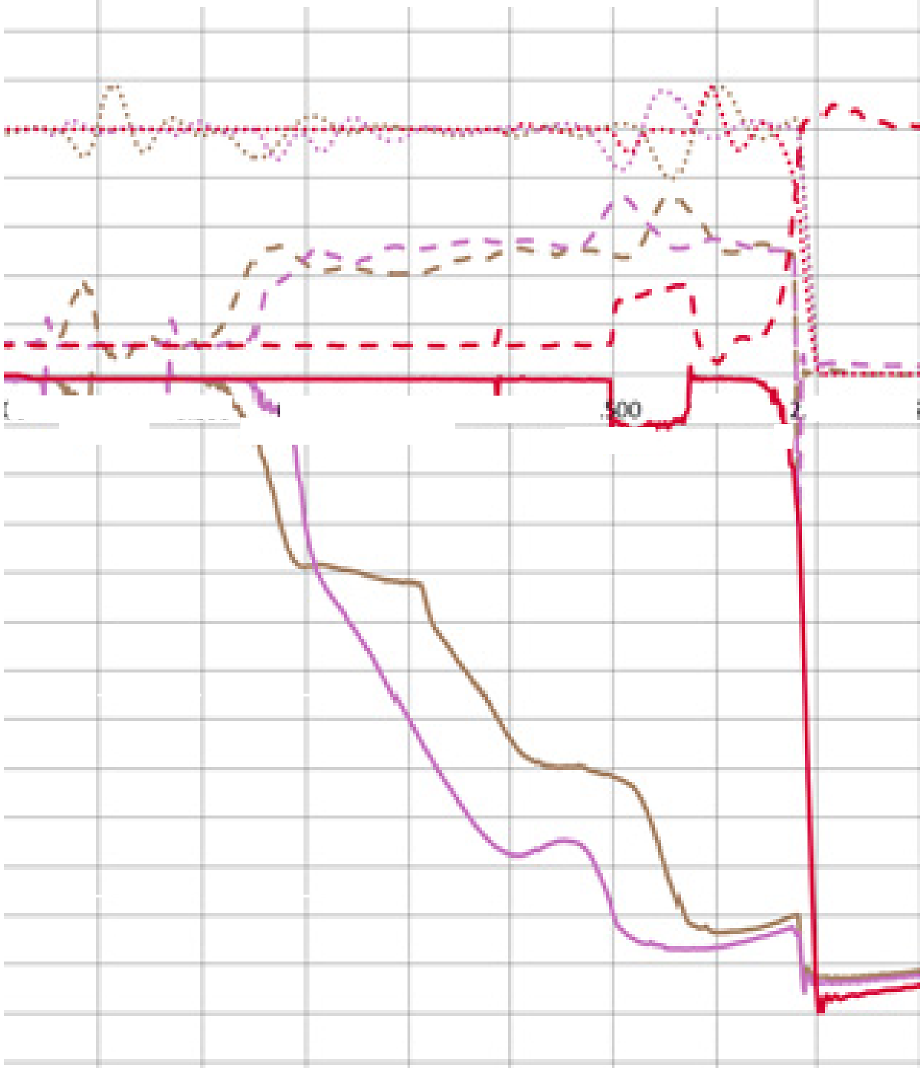
Current Status

- Took this process from scratch to Implemented on the SLS Rocket within two years.
- Appling this same versatile development methodology to investigate the Self Reacting Friction Stir Weld Process.

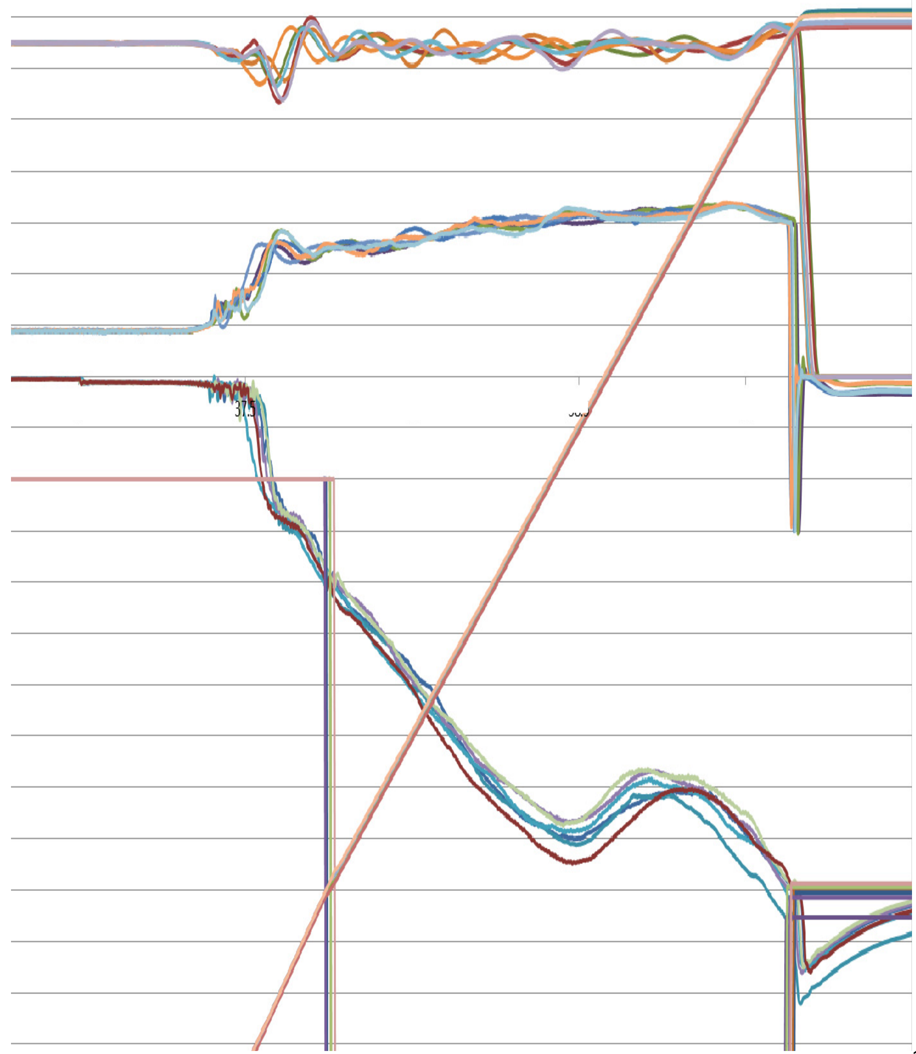
Backup

Tool Feedback Methodology Comparison

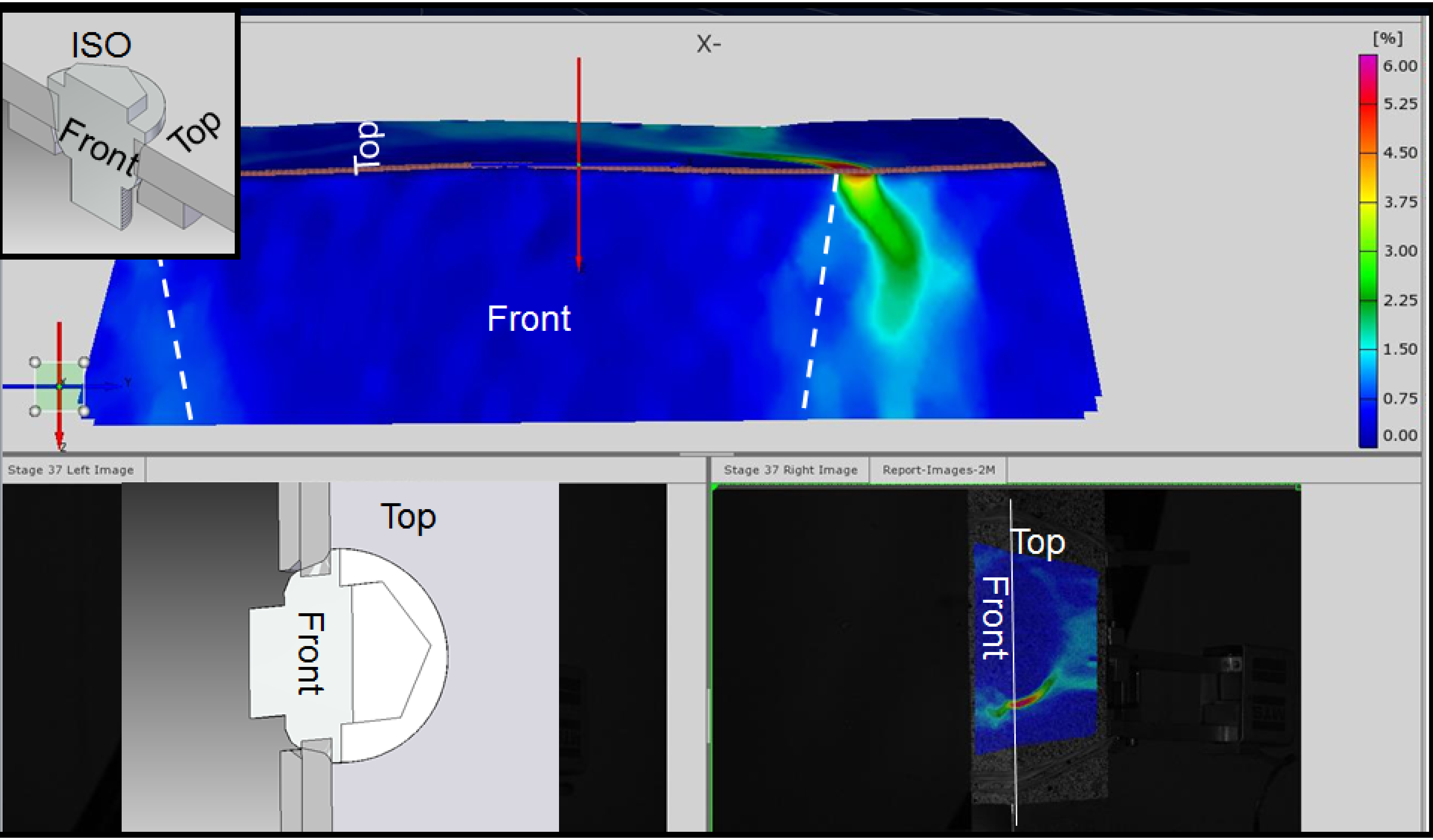
Using only Mechanical Test Methodology



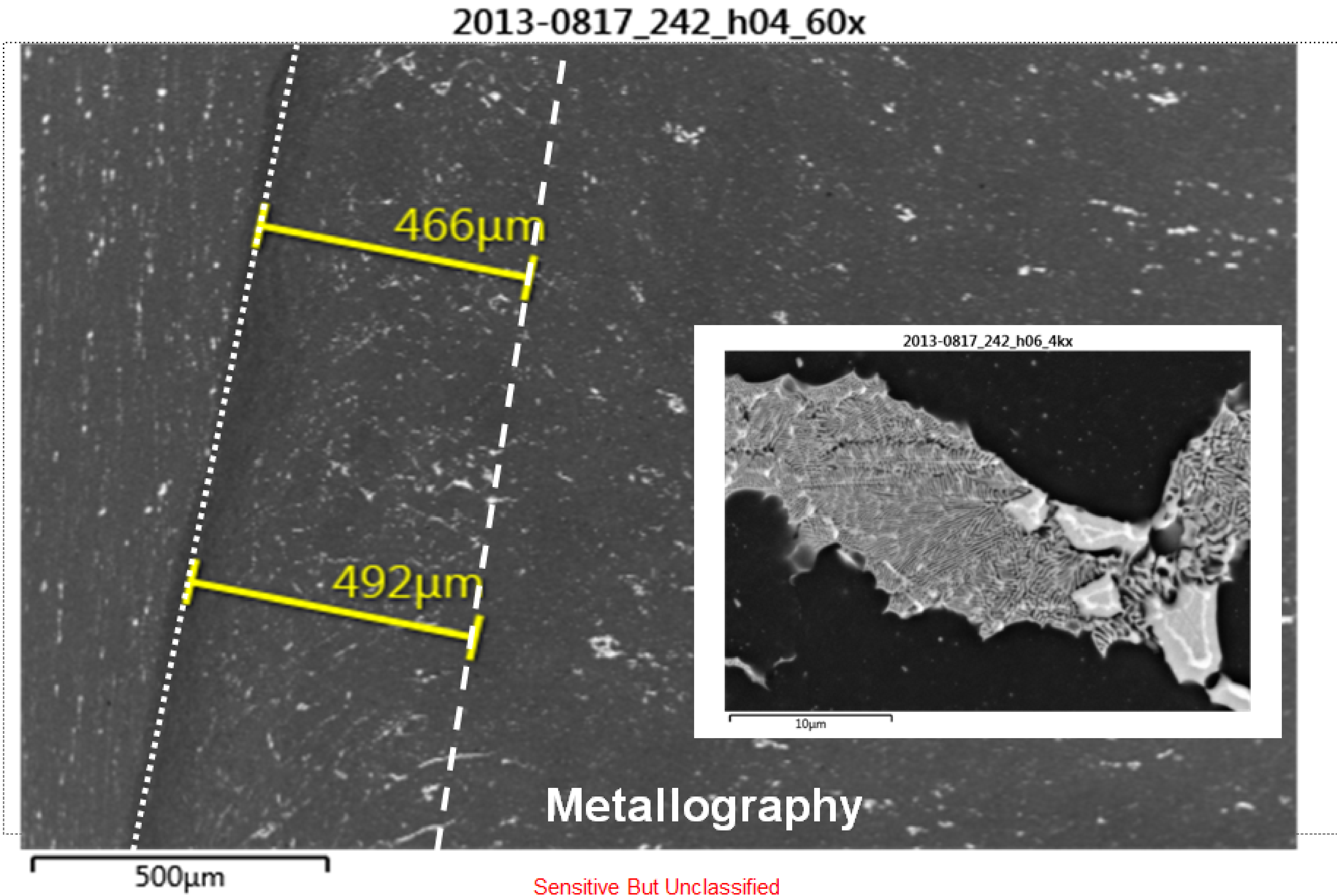
Using Tool Feedback Methodology



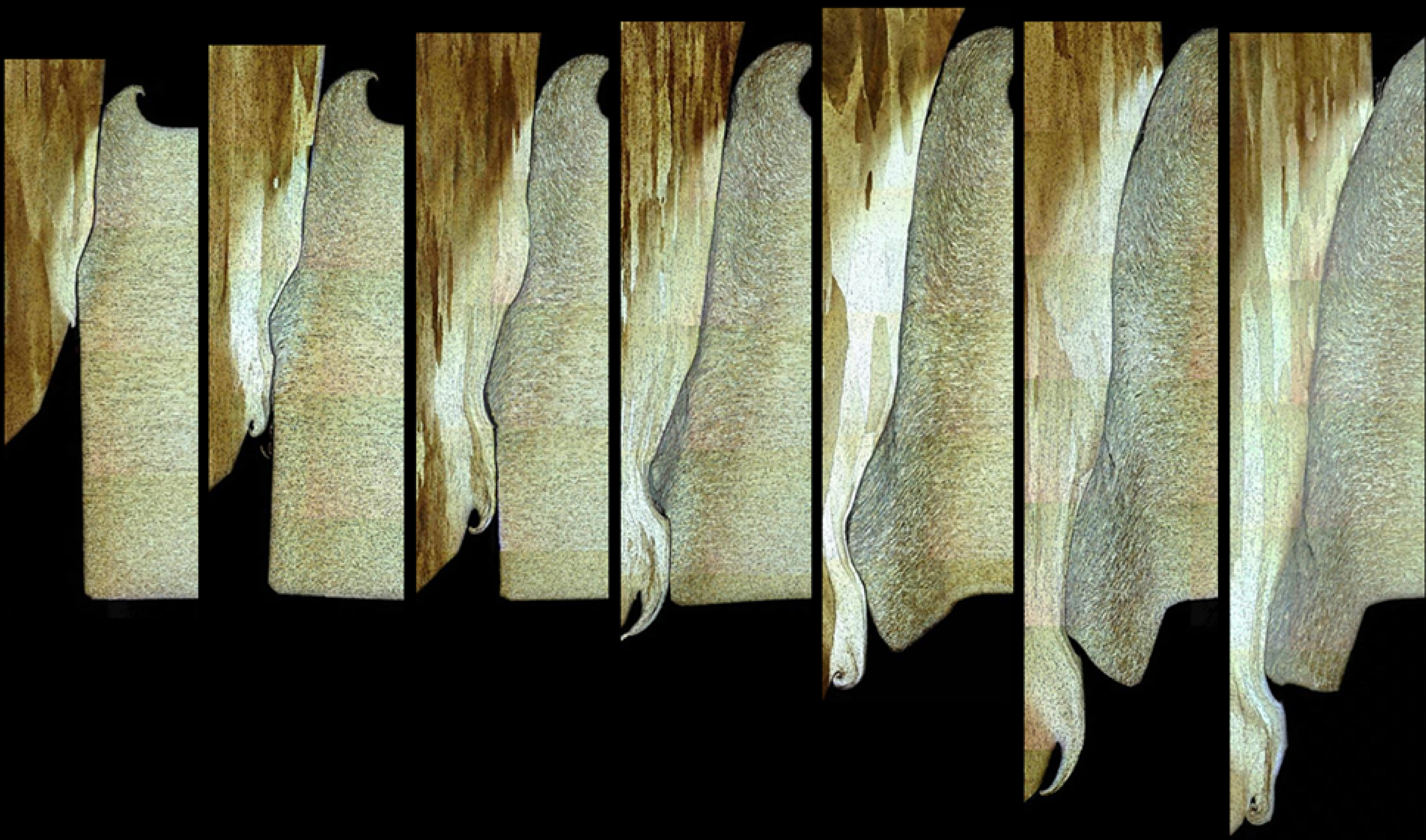
Strain Propagation (ARMIS)



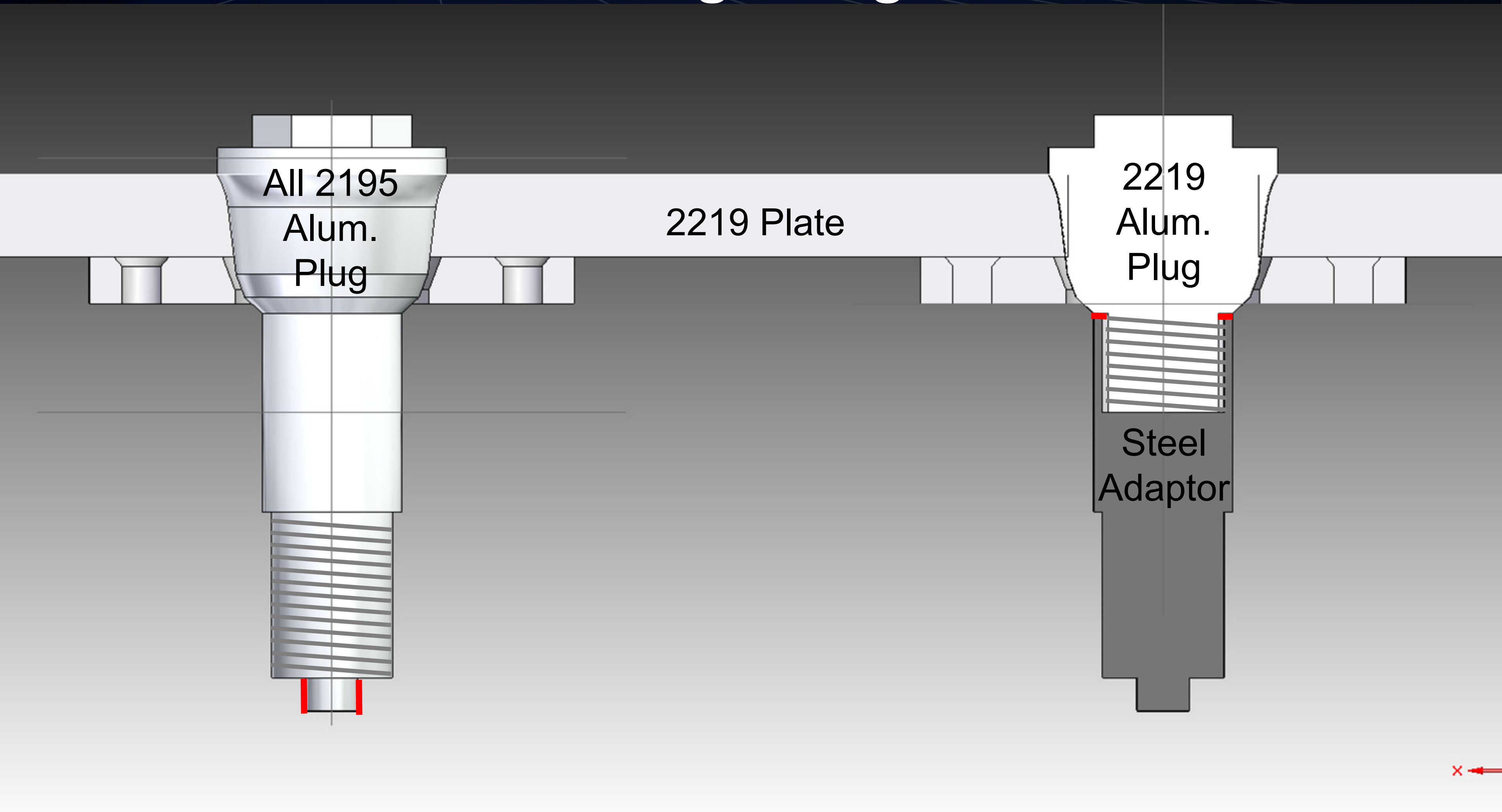
Incipient Melting Analysis



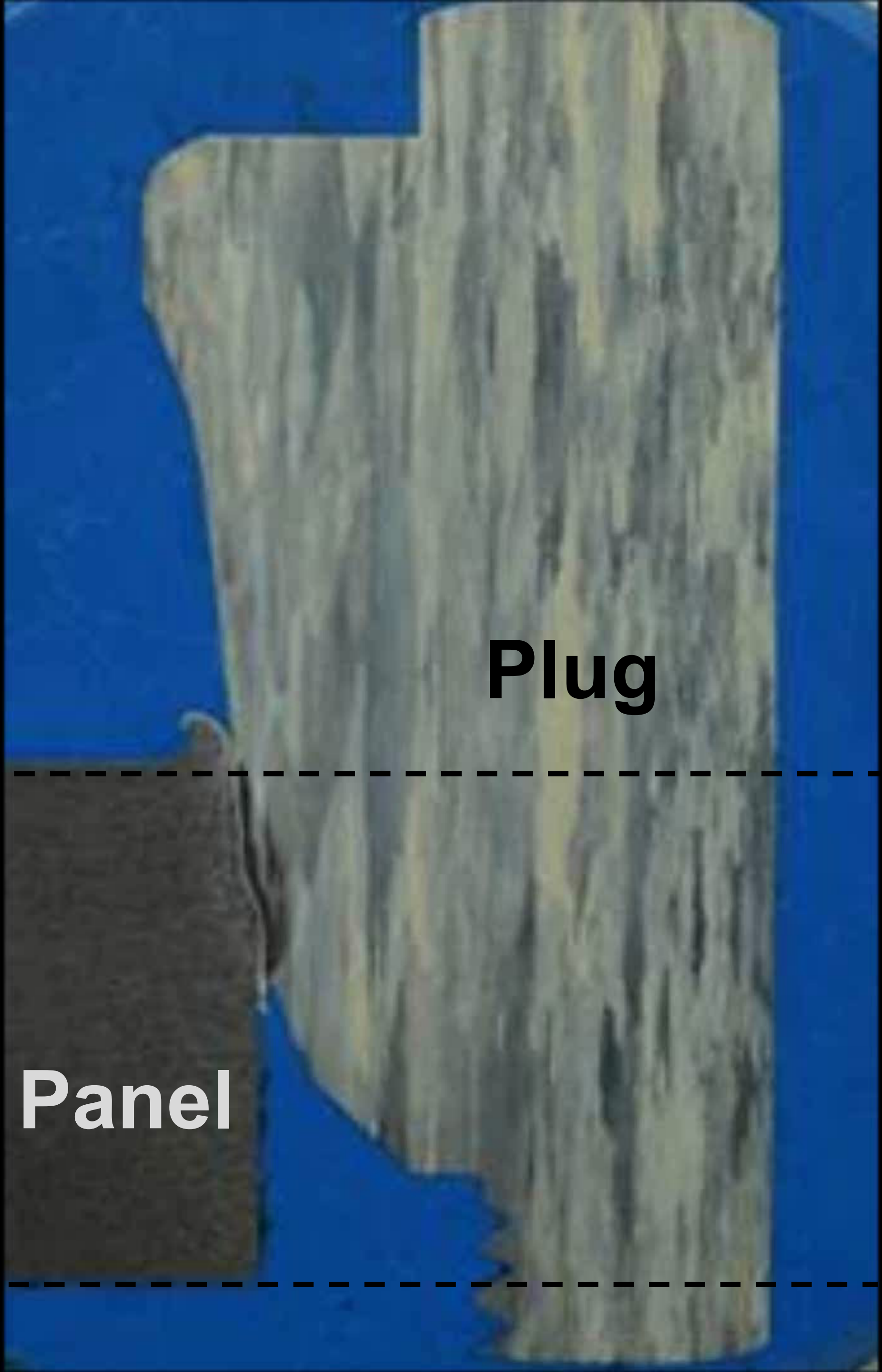
Full Macro animation



New (reverse engineered) Plug Design



Used a steel adaptor instead of a solid aluminum plug.
Replaced the 2195 material with 2219 material for the plug and.

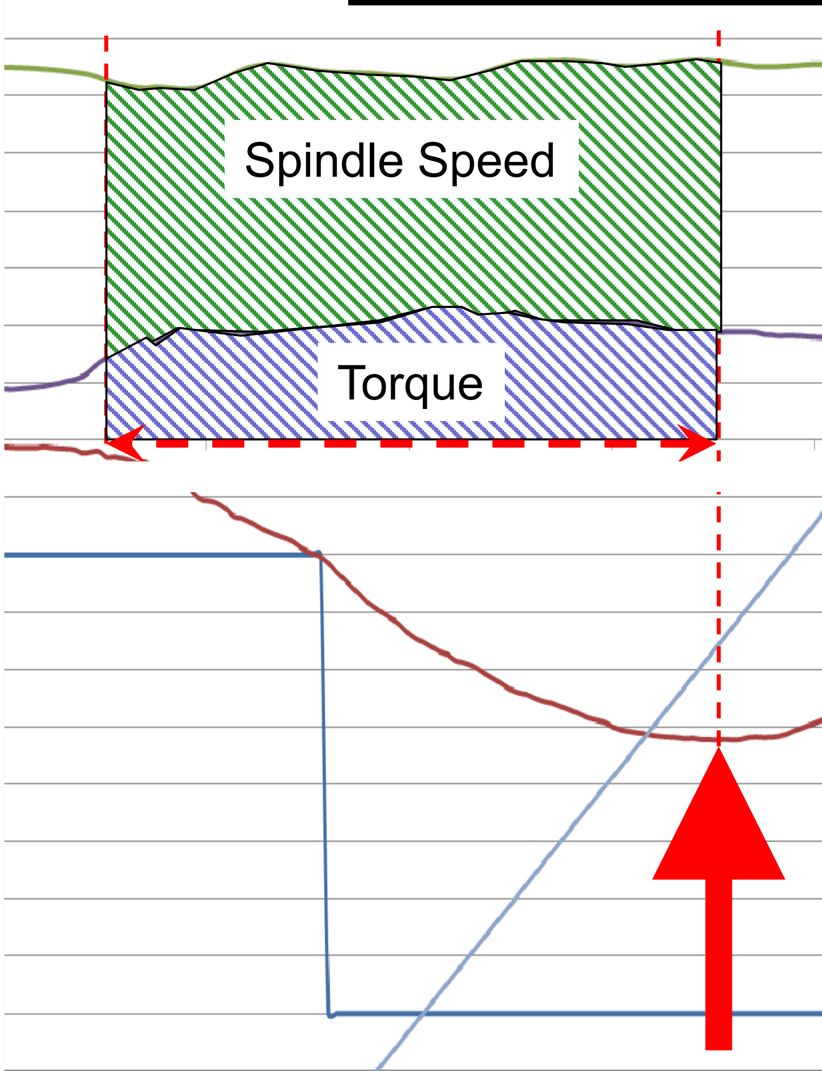

Plug
Panel

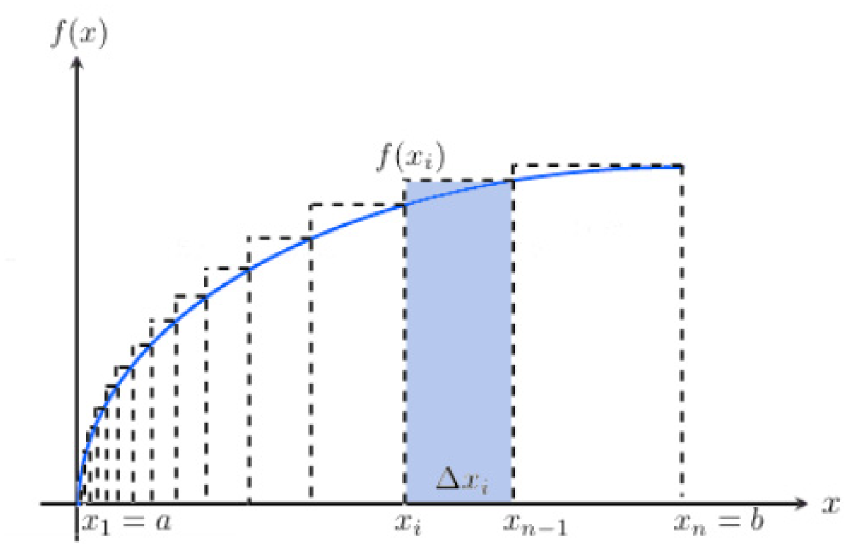
Current Plug Design

Necked Plug

Stage III: Heat Input

$$\Delta E = (\tau \times \omega)t$$

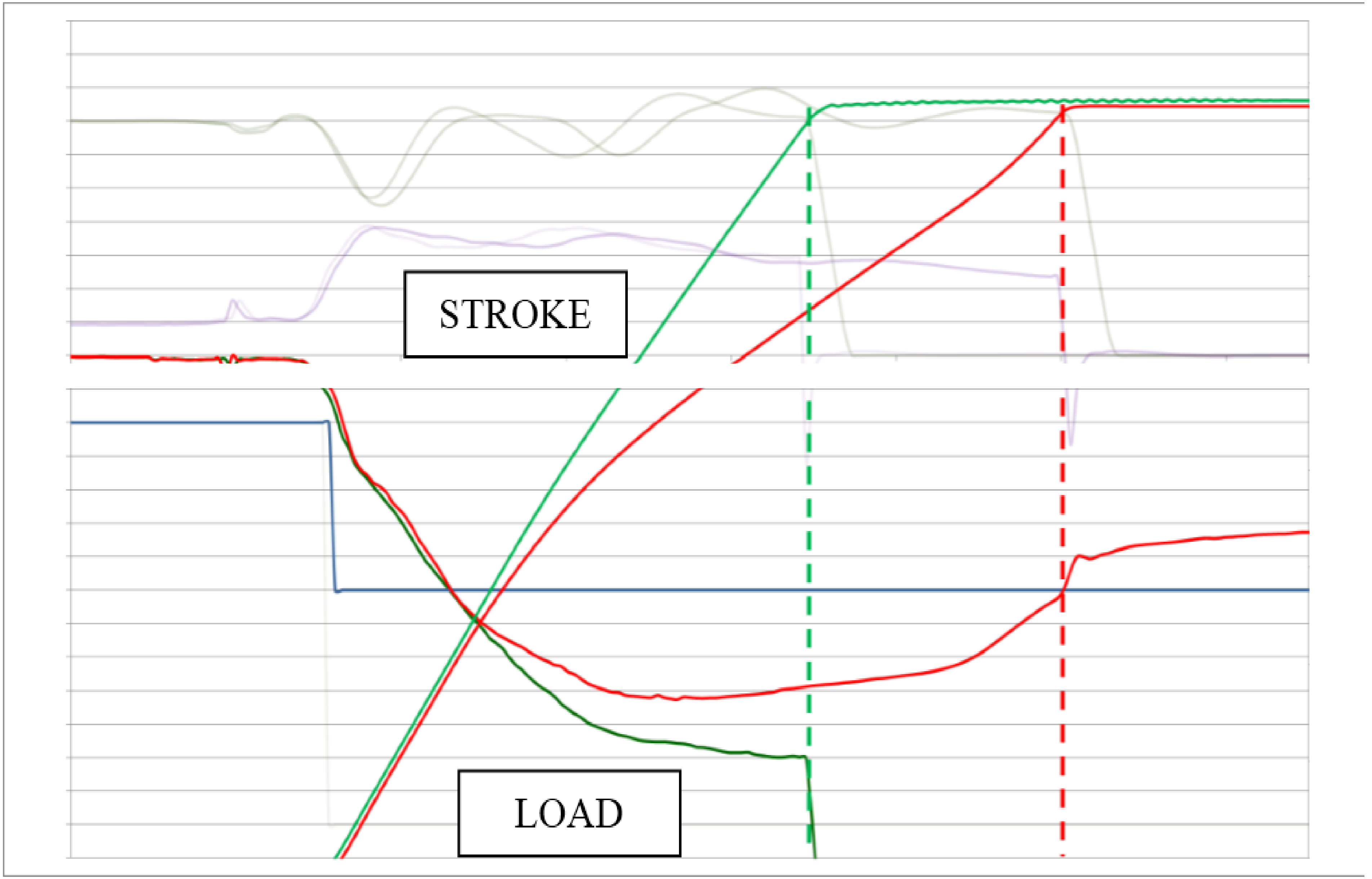




$$\text{Area under curve } f(x) = \int_a^b f(x)dx = F(b) - F(a) = \lim_{n\to\infty} \sum_{i=1}^{n} f(x_i)\Delta x_i$$

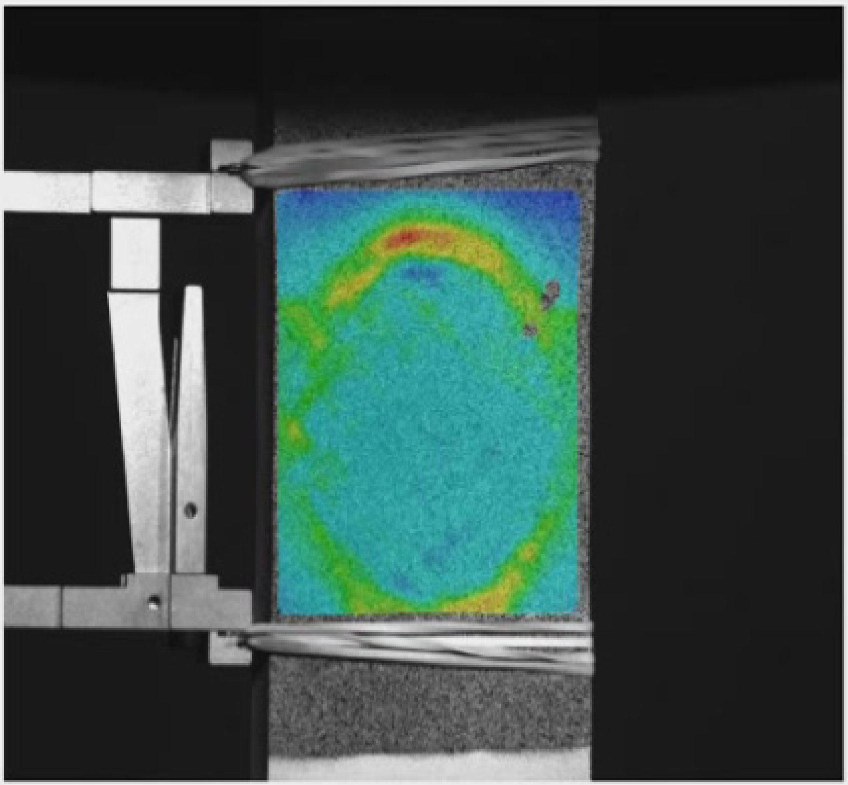
(method of exhaustion)

Load Control (Load Limit)

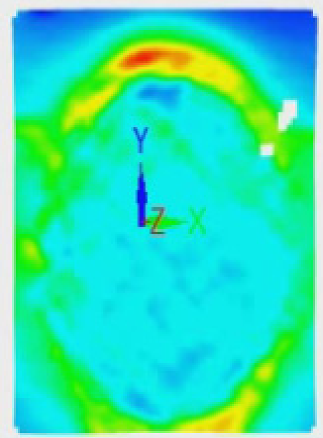


Load “Trigger”

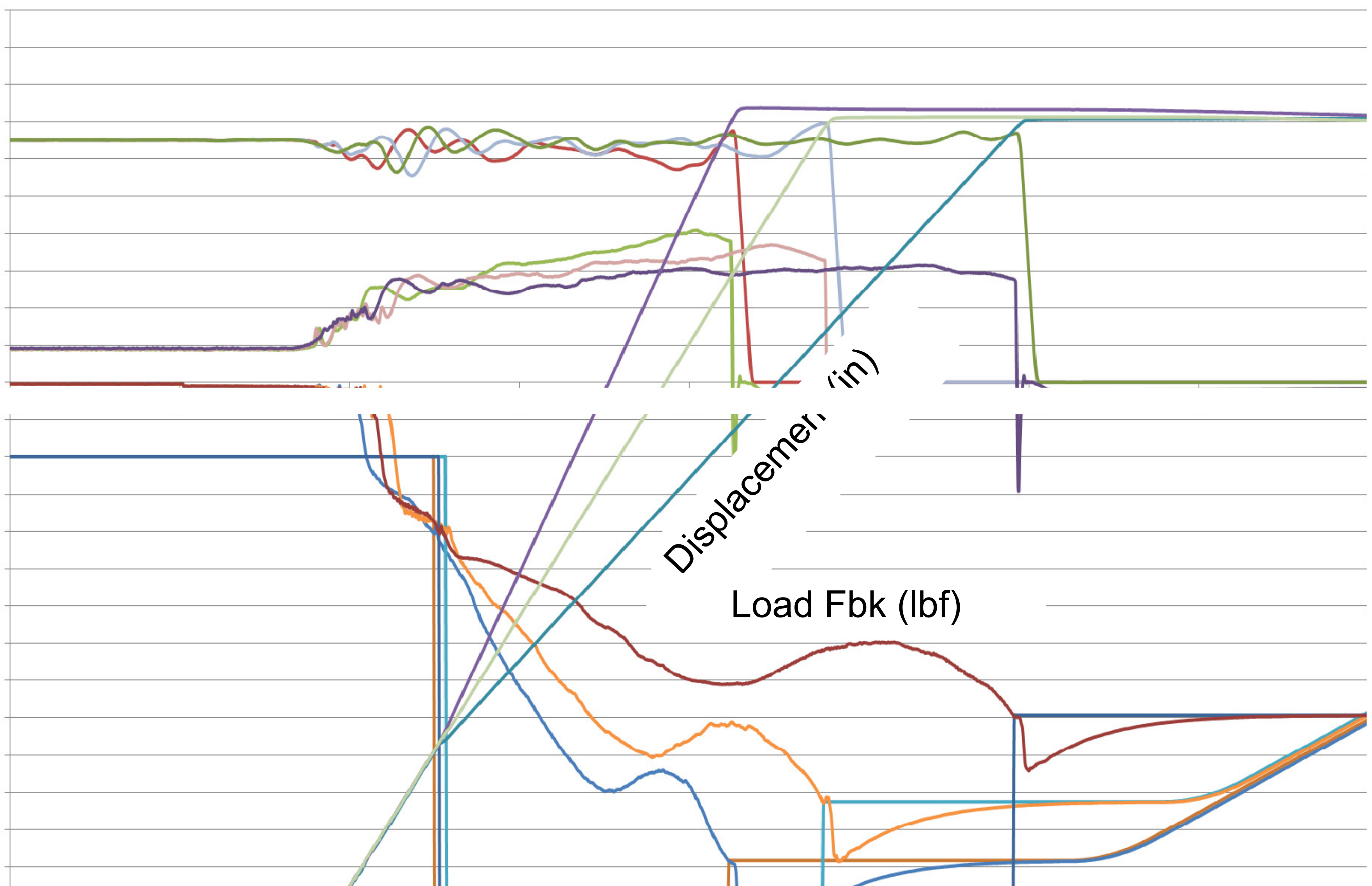
Mechanical Test with Aramis



Major Strain

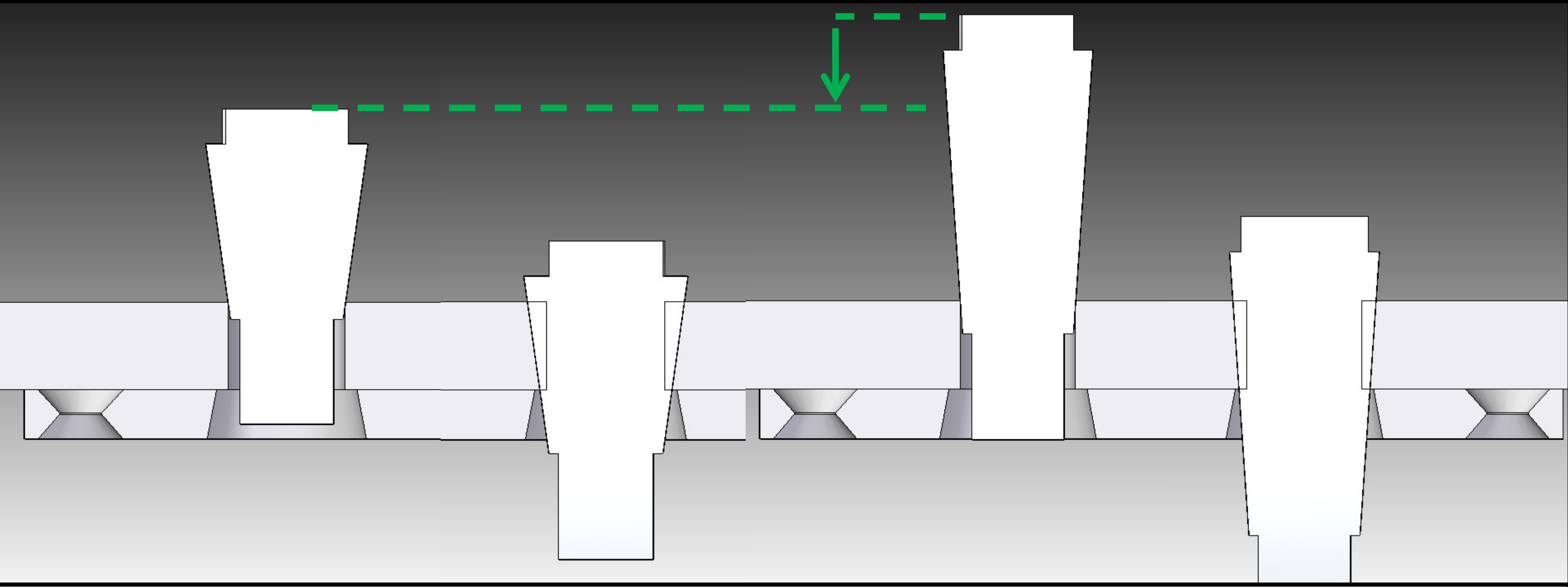


Reverse Engineered Process



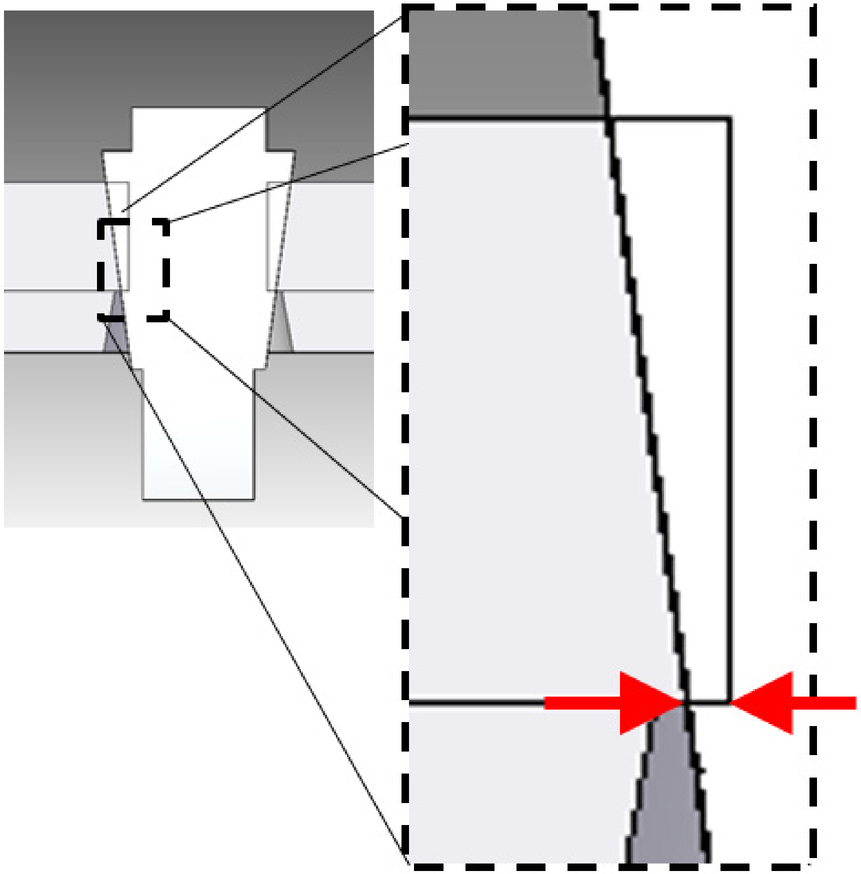
Able to Back Engineer the process.

STAGE III: HEAT INPUT



A smaller angled plug requires greater stroke for same minor diameter ligament

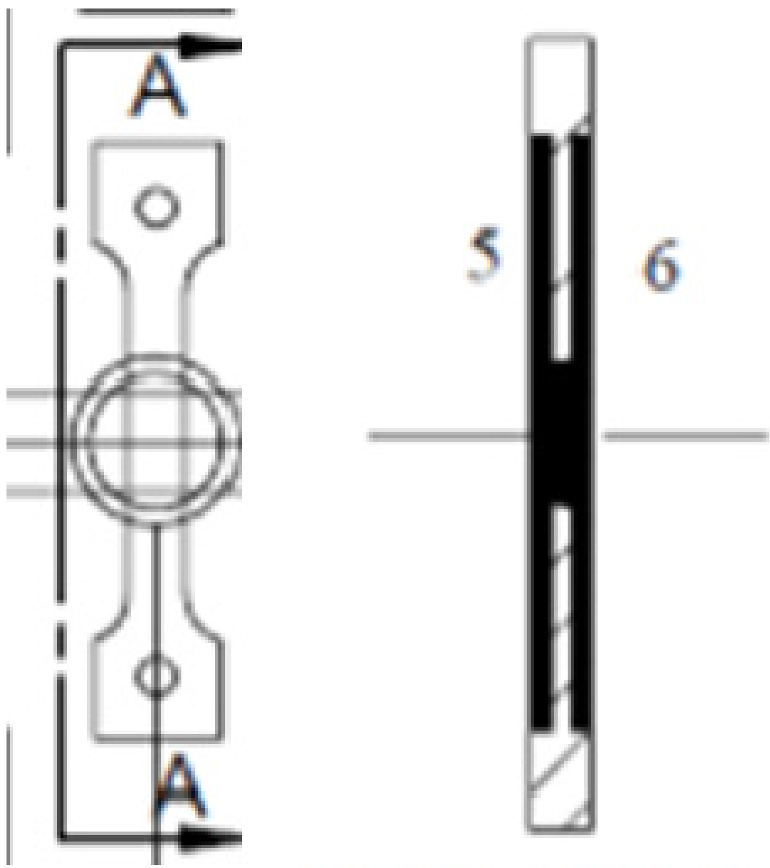
Minor Diameter Ligament



$$lig_{min} = (Displacement - Plate\,Thickness) \times \tan(Plug\ Angle)$$

The smaller the angle the greater the stroke for the same minor diameter ligament

Bond Specimens



SECTION A-A